Dark Matter*

PAX 2022

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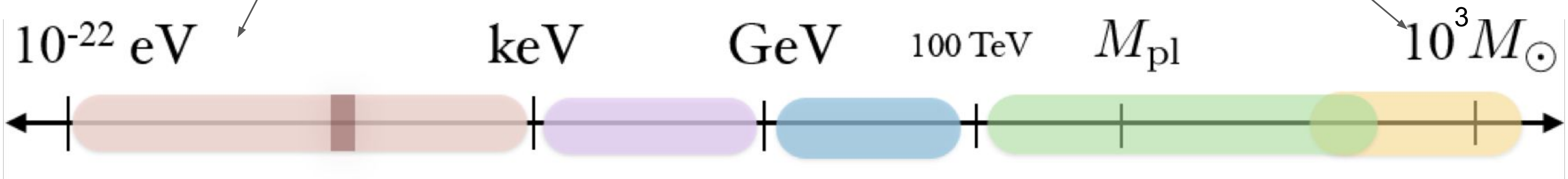
*and other new physics

Dark Matter

Black hole sizes

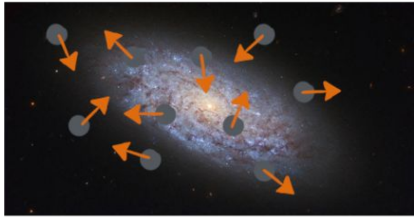
Black hole masses



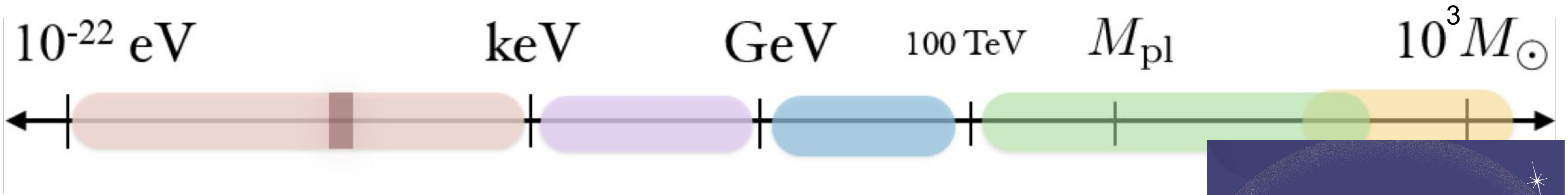
Too fuzzy

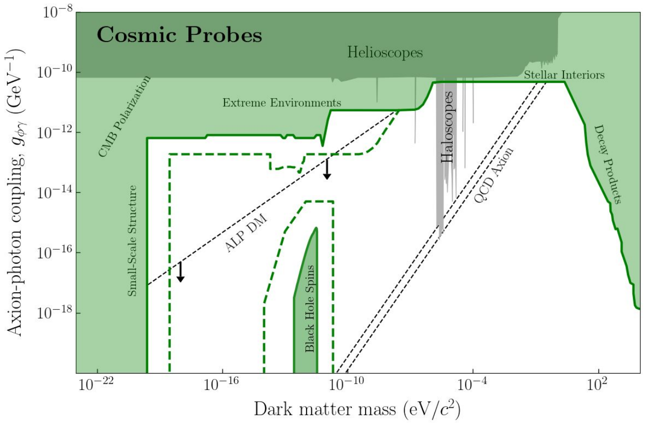
Too granular

~90 orders of magnitude!



Dark Matter





Credit: Alex Drlica Wagner for Snowmass cosmic frontier report

Black Holes and Neutron Stars create unique environments to probe otherwise inaccessible parameter space

Credit: NASA's Goddard Space Flight Center

Potential questions to keep in mind

- **Theory**: is the underlying model consistent?
- **Production mechanism**: how do the new particles/objects get produced in the early universe or the local environment?
- **Other constraints**: are GWs the first place we expect to detect these new particles/objects?

Things we know for sure:

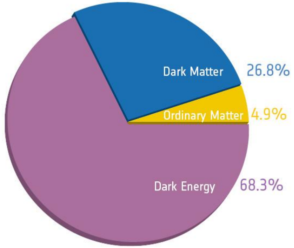
- Dark matter gravitates
- There is a lot of it [a small fraction in compact objects is still a lot of objects]

But: GWs discovery potential for new physics, even new physics that does not explain 100% of the dark matter

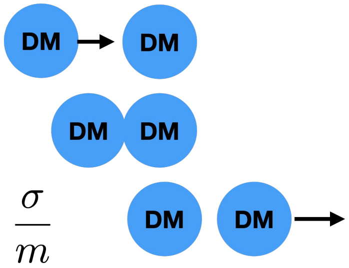
- New objects (much richer than PBH)
- Shifts to population aspects of stellar-process objects
- New environmental effects
- New routes to particle production

Model classification: most astrophysically/cosmologically important interaction

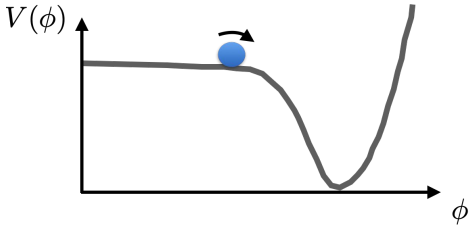
Cold Dark Matter/WIMP:
Achieve relic abundance



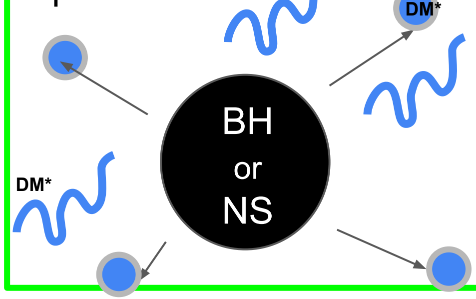
DM - DM elastic (“SIDM”)



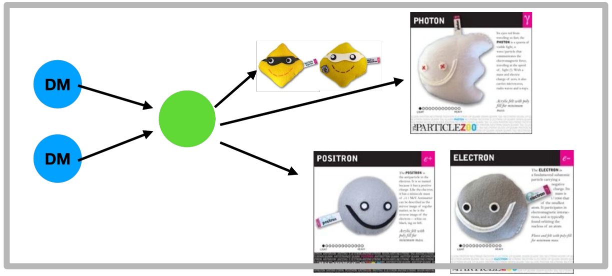
Primordial black holes:
inflationary physics on top of
this picture



Compact object DM*
production

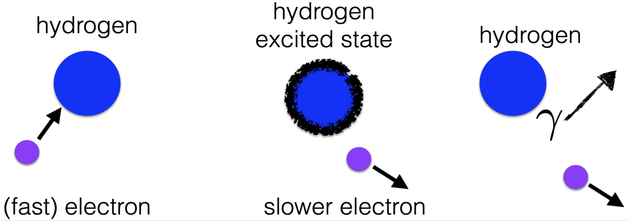


DM - SM



DM - DM, dissipative

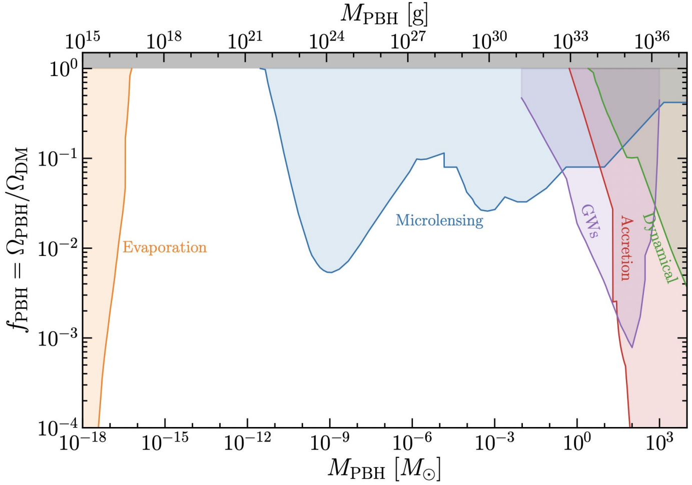
Example: collisional excitation



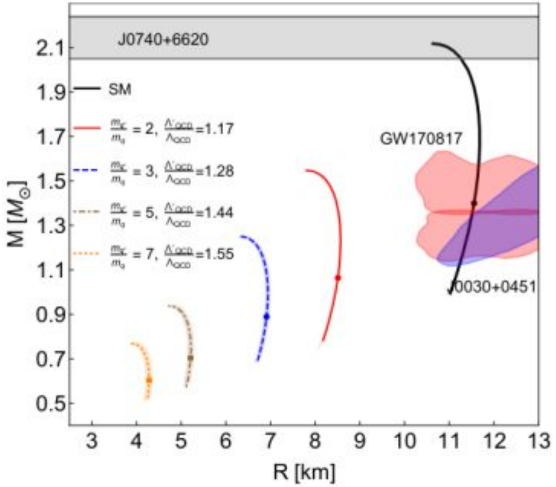
Science Case: Gravitational Wave Probes of Dark matter

- **New objects**:
  - Black holes/neutron stars/white dwarfs formed from dissipative dark matter
  - Dark matter induced collapse of neutron stars – signal from collapse or merger
  - Primordial black holes - directly observe PBH binary mergers, or the stochastic gravitational wave background signal from their formation

Green & Kavanagh (2020)



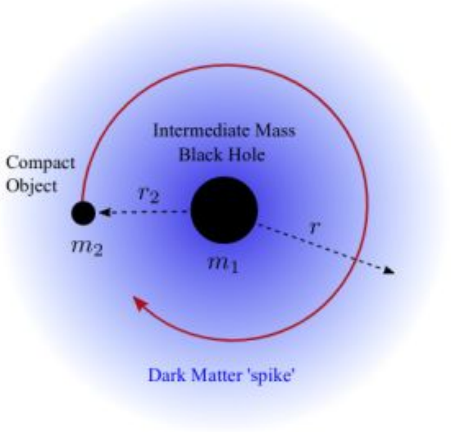
Hippert, Setford, Tan, Curtin, Noronha-Hostler, Yunes (2021)



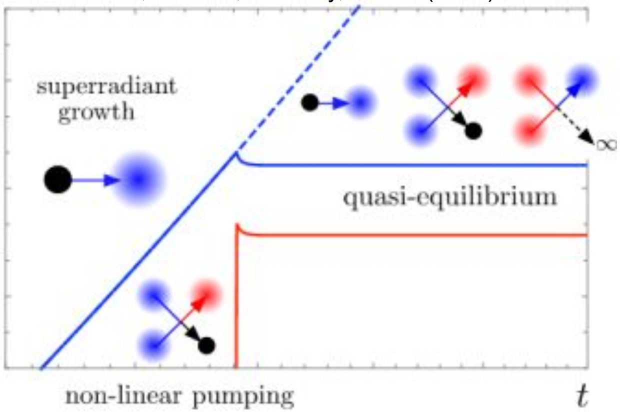
Science Case: Gravitational Wave Probes of Dark matter

- **Changes to merger dynamics:**
  - Cold, collisionless dark matter spikes impart dynamical friction effect on gravitational waveform of intermediate/extreme mass ratio black hole binaries
  - Ultralight boson black hole superradiance – spin measurements and GWs from cloud oscillations
    - Gravitational atoms - signatures of cloud ionization, accretion and resonances in gravitational waveform of intermediate/extreme mass ratio black hole binaries

Kavanagh, Nichols, Bertone, Gaggero (2020)

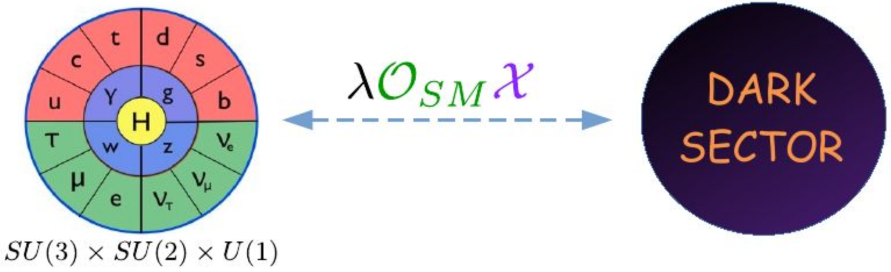


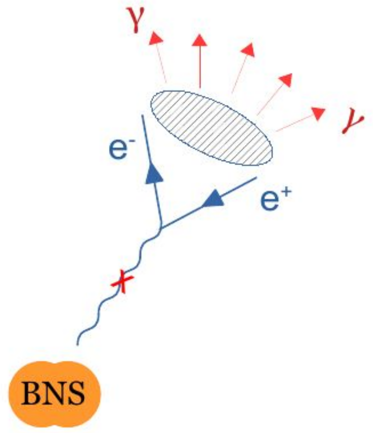
MB, Galanis, Lasenby, Simon (2020)



Science Case: Gravitational Wave Probes of Dark matter

- **Particle production from mergers**
  - Search for unstable dark sector particles produced in the hot remnant after a BNS merger.

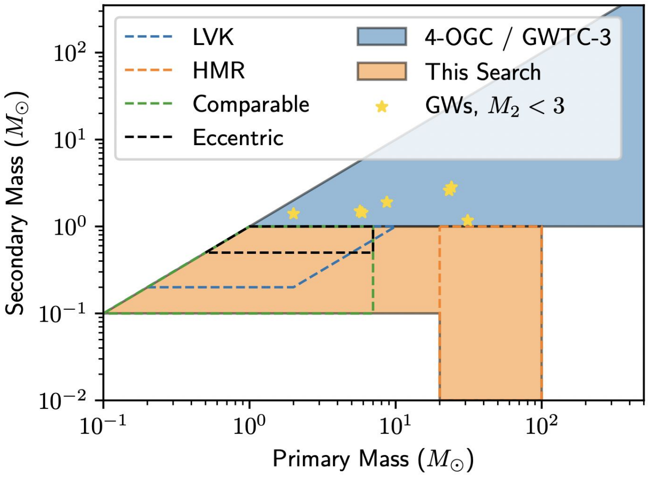


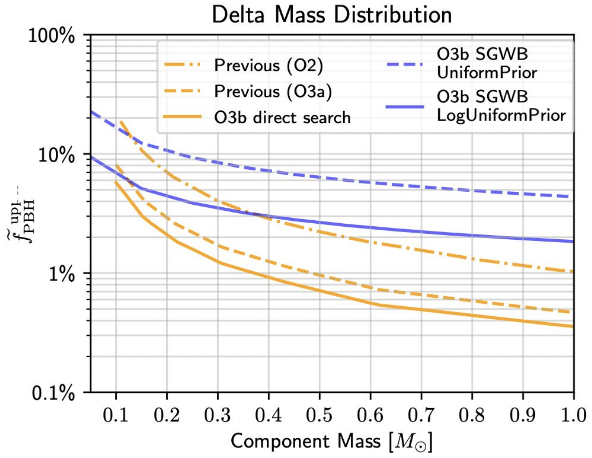


Diamond & GMT (2022) – also Fiorillo and Iocco (2022)

Dark Matter & GW: Facilities needed (sub-solar so far)

- New objects:
  - Better sensitivities for stronger constraints on new particles and to probe lower merger rates of solar mass objects, as well as sub-solar mass objects
  - Kilohertz frequency detectors for neutron stars/low mass black holes
  - LISA frequencies also well-positioned for SGWB signature of asteroid mass PBHs (last remaining window where they can make up all of the dark matter)

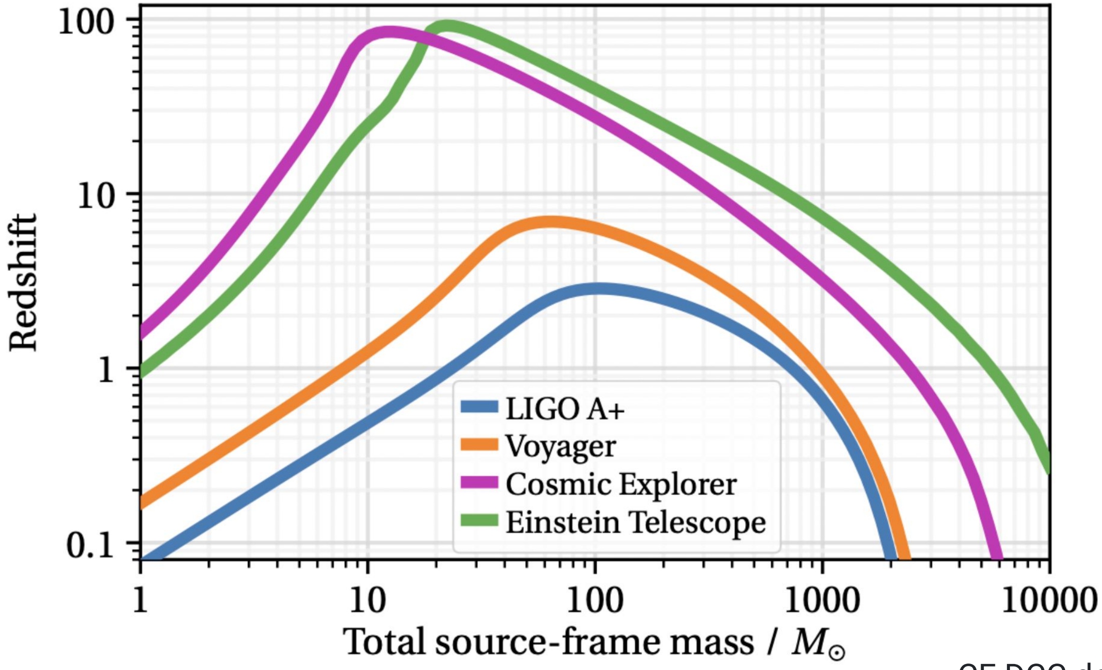




Nitz & Wang 2022

Dark Matter & GW: Facilities needed

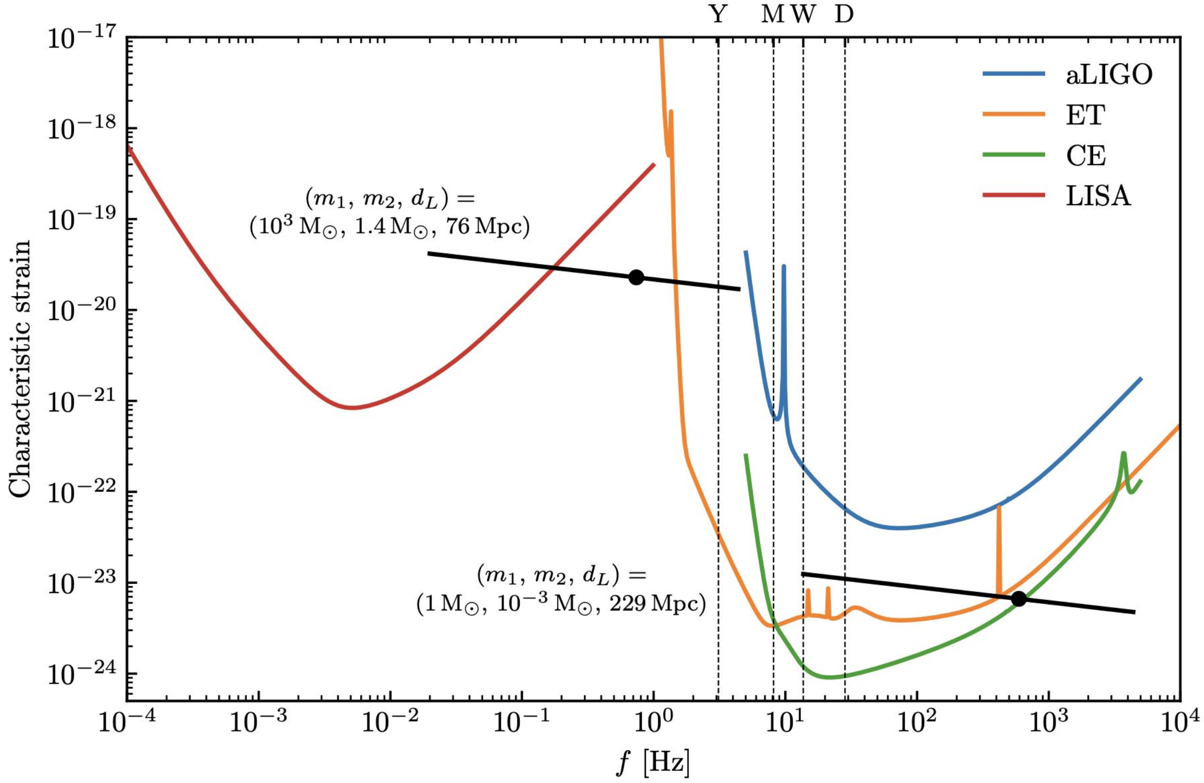
- High redshift observation would be a ‘smoking gun’ for a non-standard origin



CE DCC document

Dark Matter & GW: Facilities needed

- Changes to inspiral dynamics
  - Long durations signals to detect environmental effects: need systems to be in band for a long time (order weeks - years) and want low frequencies
- Space-based (LISA) for intermediate mass black holes
- Multi-band searches?
- Particle production from mergers
  - Lower frequencies to detect earlier stages of BNS with better localization would allow pointing x-ray (maybe future MeV) telescopes to search for multi-messenger signals of dark sectors

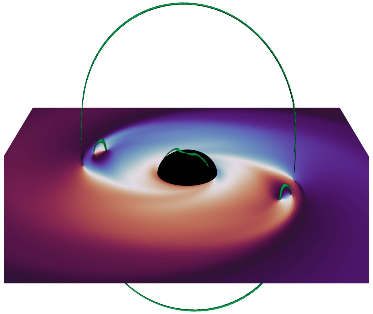


Cole et al. 2022

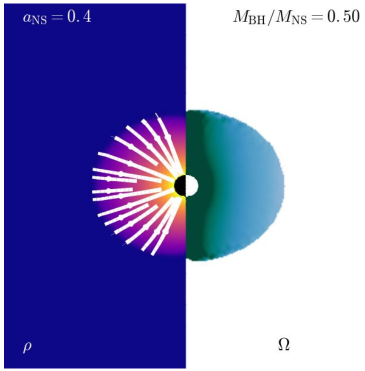
Dark matter and gravitational waves: Theory next steps

- New effects and new objects: For many potential sources still understanding basic predictions/new phenomena.
  - Improved modeling of structure and compact object formation in dissipative dark matter models
  - When do dissipative models produce subsolar black holes? Supermassive black holes? Both?
  - Better understand how nonlinear interactions/coupling to other matter can complicate/enrich observational signatures (e.g. multimessenger sources).
- Closing the gap between theory and observational searches: For some sources we have better understanding, but still lack detailed models.
  - Binary waveform modelling: including relativistic effects, spins, orbital eccentricity
  - Need to show that environmental effects are not degenerate with anything in standard vacuum GR systems
  - Develop waveform models suitable for performing searches
  - Multimessenger signatures

In many cases, phenomenology is more complicated than standard sources, but modelling is much less developed.



WE (2022)



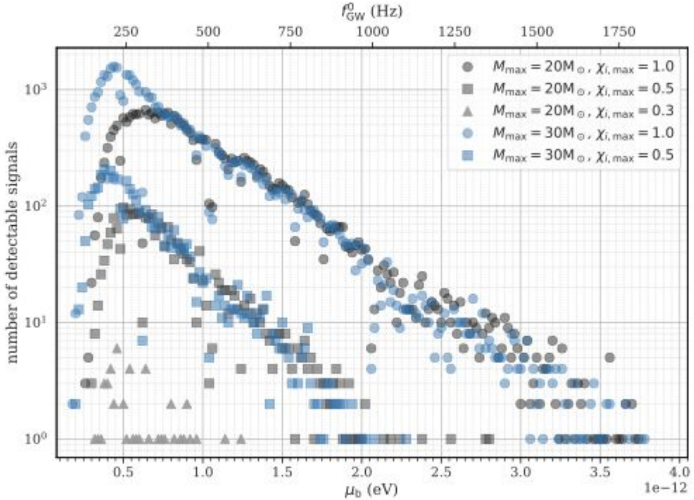
WE & Lehner (2019)

Dark matter and GWs: Questions for the community

- How much effort should we invest on the theory/modelling side in coming up with accurate predictions? How much will this improve searches?
- How much effort to invest in the data analysis side?
  - In some cases dealing with hour/week/month/year-long signals
  - May not fall in standard search “box” e.g. intermediate between CBC and continuous wave
  - Search strategies: match-filter versus continuous wave… or something new?
- Do we expect/how do we deal with multi-messenger signatures?
- How do can foster more collaboration between particle phenomenology and GW astronomy communities?
  - How to decide what are the most interesting signatures/directions to pursue?
  - How to connect observations (or lack thereof) to underlying dark matter/new physics parameters?

Gravitational Wave Signals

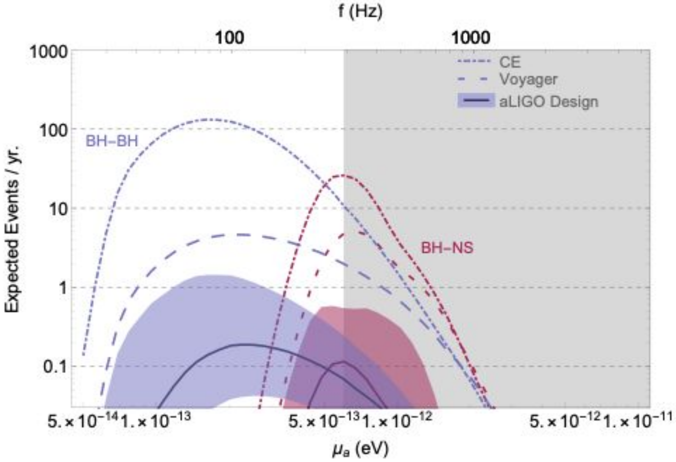
Current searches:



A. Arvanitaki, **MB**, X. Huang (2015)

- **Weak, long signals** last for ~ million years, visible from our galaxy
- Up to 1000 signals above sensitivity threshold of Advanced LIGO searches today
- Large density of signal per search frequency bin can degrade existing search efficiency

Future observatories:



A. Arvanitaki, **MB**, S. Dimopoulos, S. Dubovsky, R. Lasenby (2017)

- **Short, bright signals** — directed follow-up searches to BHs in mergers
- Measure BH mass, spin, and particle mass: fully study gravitational atom
- Promising at future GW observatories, methods investigations ongoing
  - M. Isi, L. Sun, R. Brito, A. Melatos (2019)

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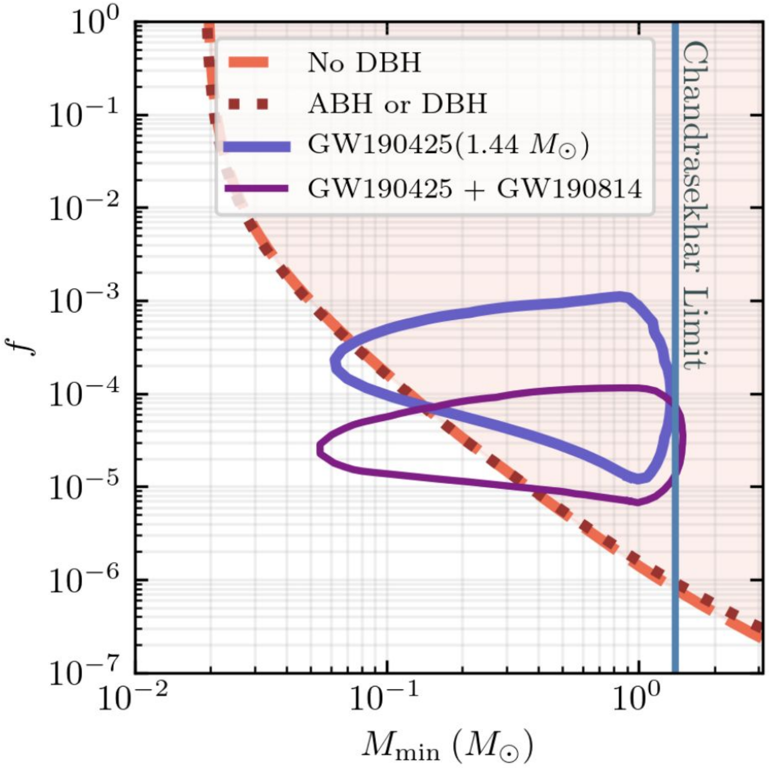
Back-up slide: Dissipative Dark Matter

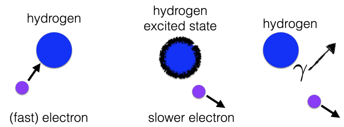
Singh et al, 2009.05209

- Most dark matter would be in CDM-like halos, some would have cooled into compact objects
- Discovering light black holes: Direct limit on heavier mass of a dark fermion
- Black hole masses more generally: dark chemistry of cooling dark matter gas



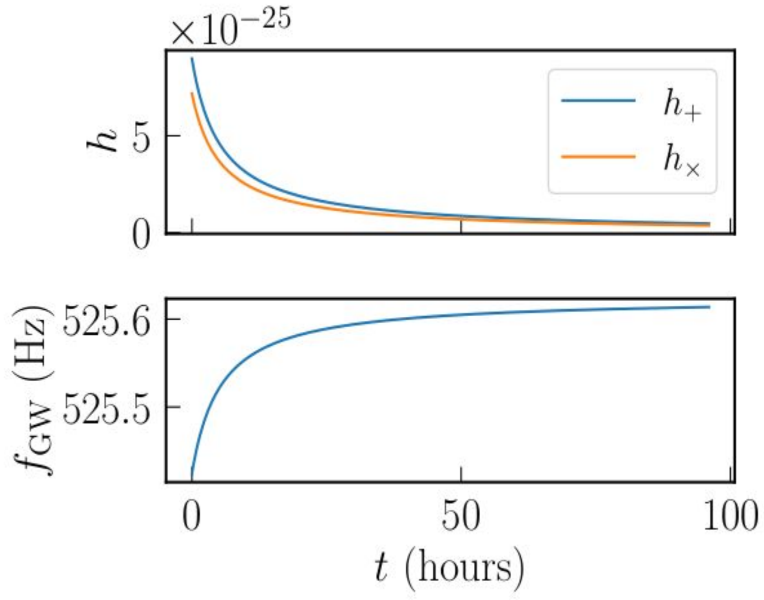
D'Amico et al 1707.03419, Shandera et al 1802.08206, Essig et al 1809.01144, Latif et al, 1812.03104,Chang et al 1812.07000; Choquette et al 1812.05088
Ryan, Radice 2201.05626 (Dark white dwarfs); Hippert et al 2103.01965 (Mirror Neutron Stars)

Example: collisional excitation



Modeling GWs from ultralight boson superradiance

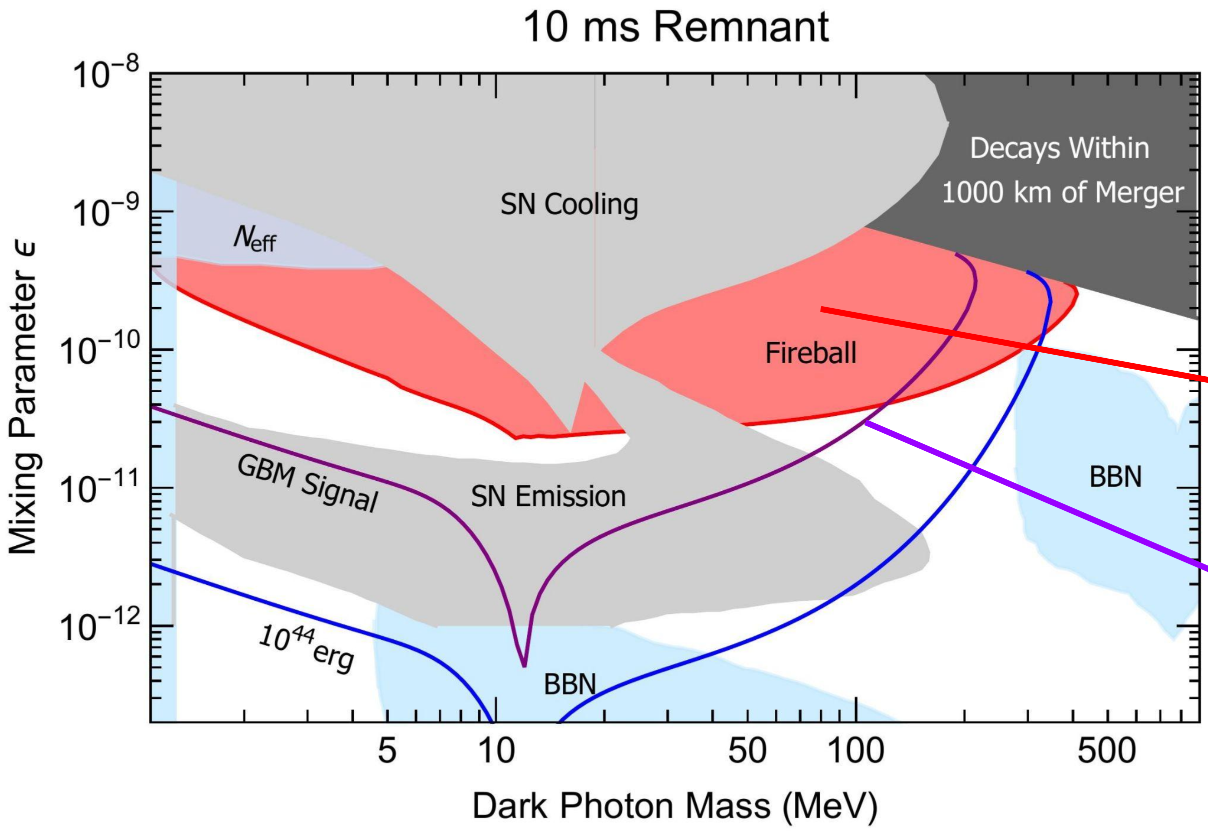
- Targeted follow-ups of merger remnants obviates need to assume source population, but need loud signal
- Loudest signals require relativistic modelling
- As cloud dissipates, leads to chirp (increase in f_{GW}) – nonlinear effect
- Not taking this into account limits the time GW can be coherently integrated (current searches assume $|df/dt| <\sim 10^{-11}$ Hz/s)

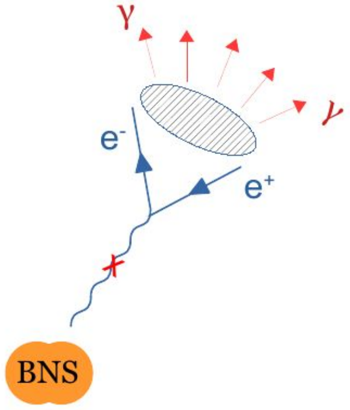


mu=10^{-12} eV; M= 20 solar masses; a=0.8; d=100 Mpc

Siemonsen, May, WE, in prep

Backup slide: BSM signals from BNS mergers



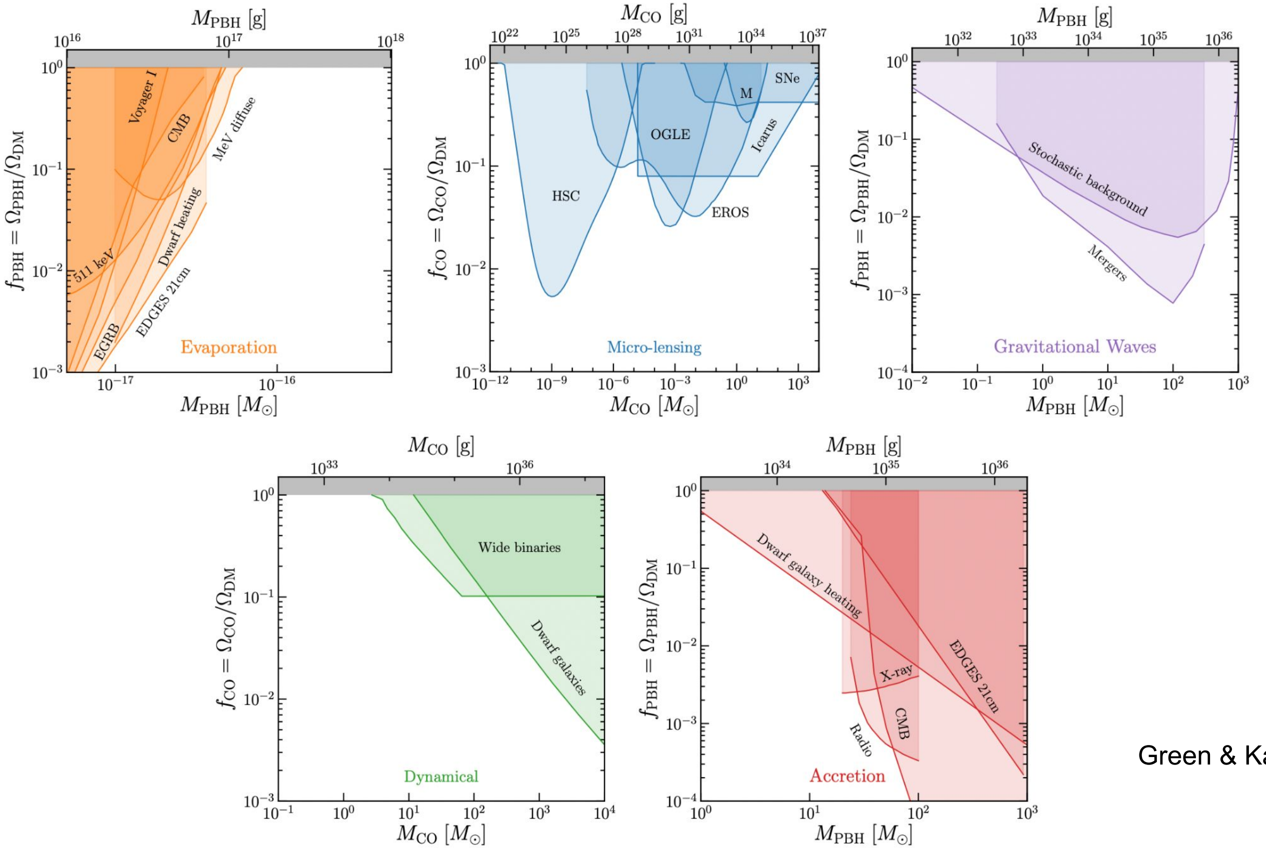


In red region gamma-ray signal is approximately thermal with T ~ 10-100 keV

Above purple line total luminosity is > 1e46 erg

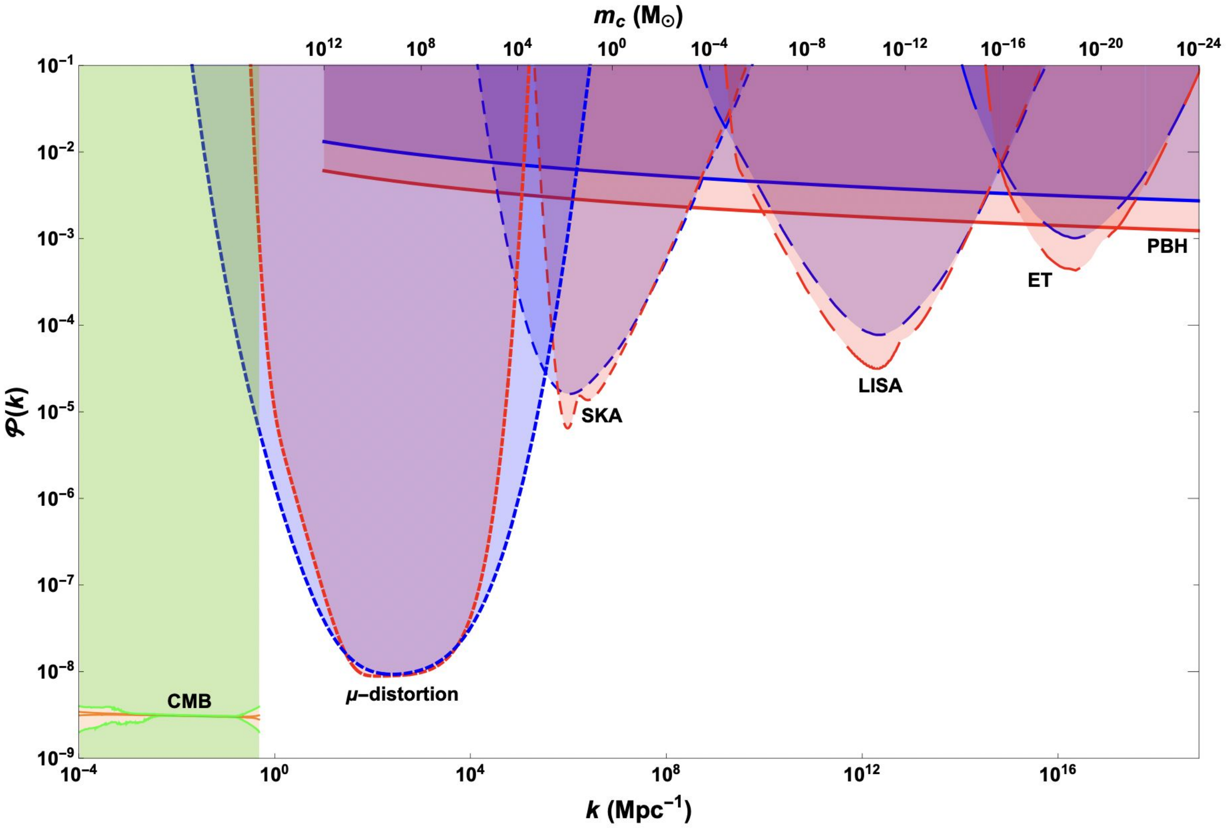
Diamond & GMT (2022) – see also Fiorillo and Iocco (2022)

Back up slide - PBHs



Green & Kavanagh 2020

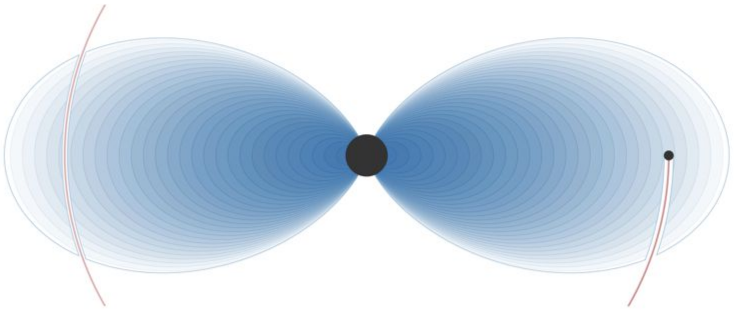
Back up slide - SGWB



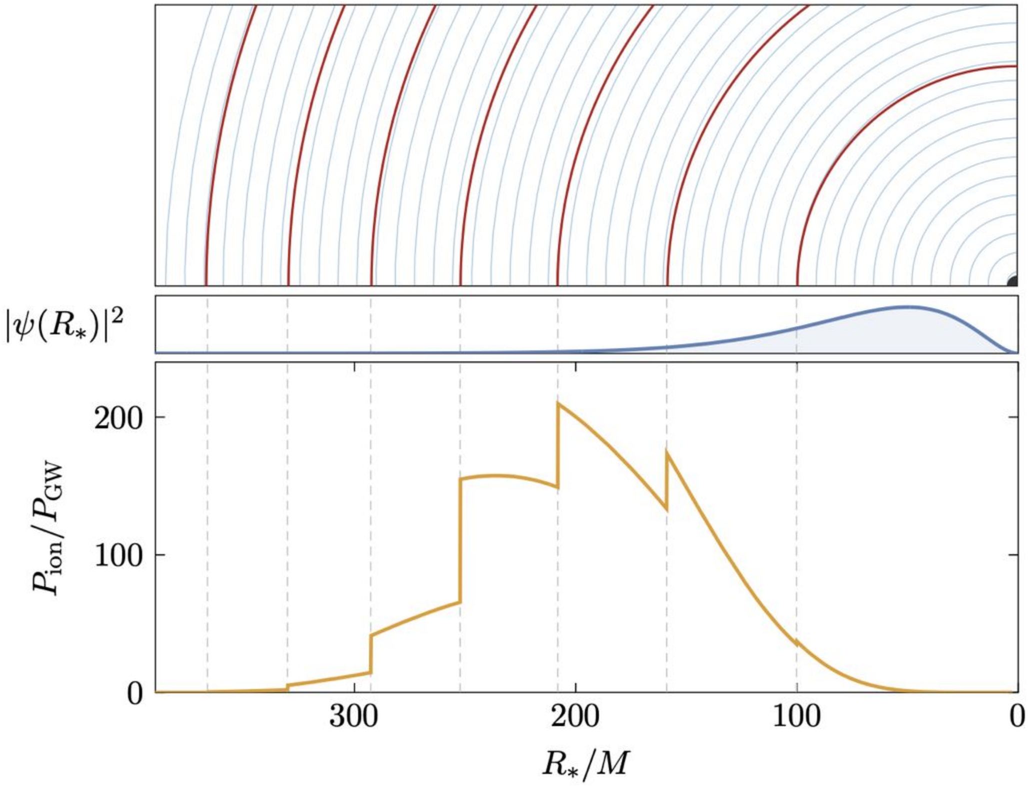
Gow et al. 2020

Back up slide - environmental effects

Ionization



Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states



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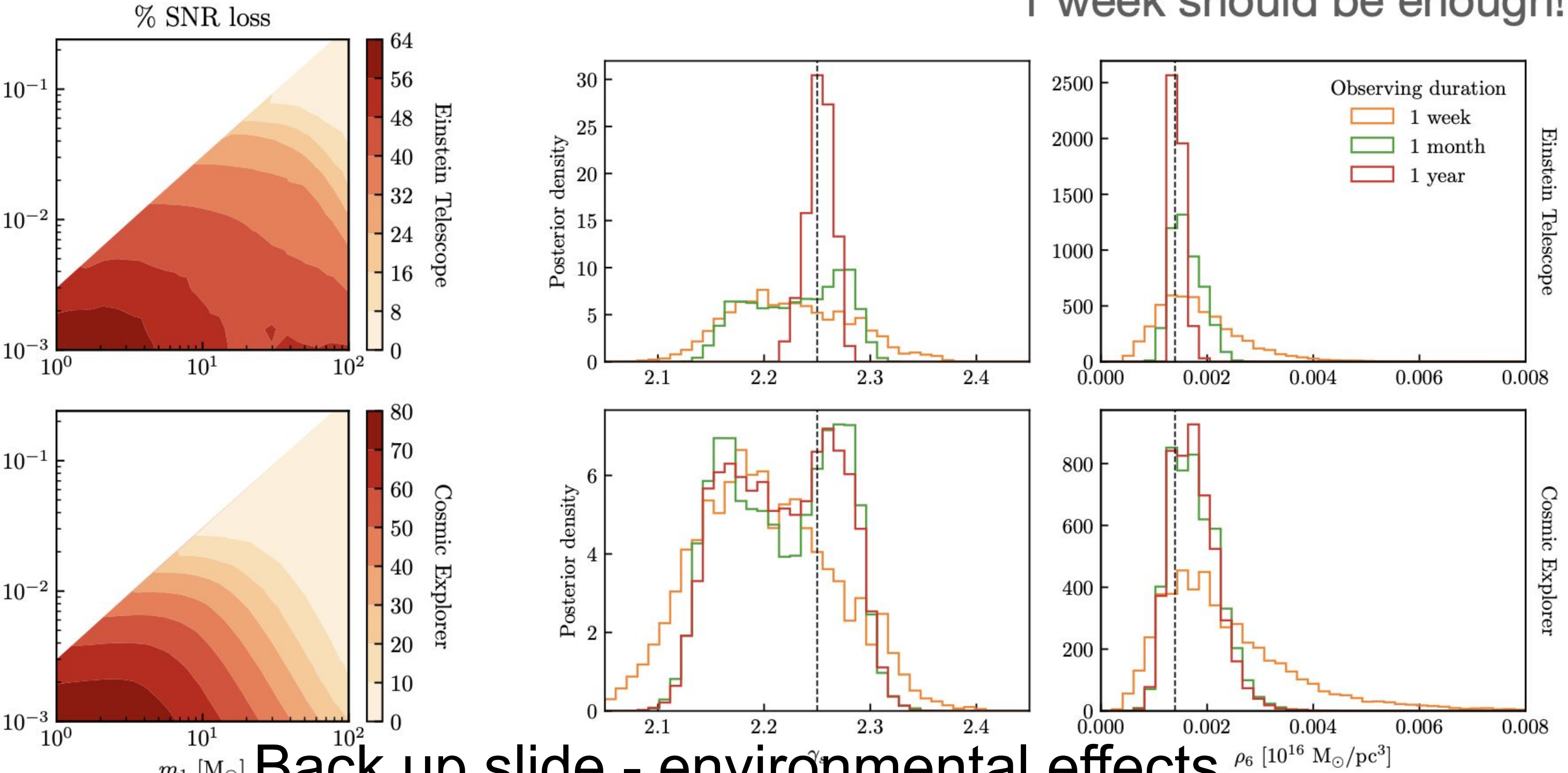
Baumann, Bertone, Stout, Tomaselli 2021

What about future ground-based detectors?

1 week should be enough!



Back up slide - environmental effects

x

Cole, Coogan, Kavanagh, Bertone in prep